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Reduction of $3\omega_0/2$ Emission From Laser-Produced Plasmas With Broadwidth Induced Spatial Incoherence at 0.53 μm

T. A. PEYSER, C. K. MANKA, S. P. OBENSCHAIN, AND K. J. KEARNEY

Laser Plasma Branch
Plasma Physics Division

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T. A. Peyser, C. K. Manka, S. P. Obenschain and K. J. Kearney

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Measurements of the $3\omega_0/2$ emission from laser-irradiated targets at 0.53 μm were made at three angles over a wide range of laser bandwidths with and without induced spatial incoherence (ISI) echelons. The $3\omega_0/2$ emission was found to be correlated with hard x-rays but not Raman spectra suggesting that the $3\omega_0/2$ radiation was due to two plasmon decay. Reduction of both $3\omega_0/2$ emission and the accompanying hard x-rays by ISI required five to ten times larger bandwidths than needed to suppress stimulated Raman scattering and stimulated Brilloin scattering.

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CONTENTS

REDUCTION OF $3\omega_0/2$ EMISSION FROM LASER-PRODUCED PLASMAS WITH BROADWIDTH INDUCED SPATIAL INCOHERENCE AT 0.53 μm

I. INTRODUCTION

Induced spatial incoherence (ISI) was first proposed as a beam smoothing technique to provide the highly uniform illumination required for direct-drive laser fusion.[1,2] ISI has been found, however, not only to provide uniform illumination but also to suppress a number of deleterious plasma instabilities associated with the reflection and absorption of the incident laser energy such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).[3,4,5] In this article, we present the first detailed experimental study of the effect of ISI on the two-plasmon decay instability as inferred from three-halves harmonic ($3\omega_0/2$) emission correlated with x-ray measurements.

The importance of beam smoothing for direct-drive laser fusion has been widely recognized especially with respect to minimizing initial perturbations that can lead to hydrodynamic instabilities and reducing filamentation that may enhance parametric instabilities. There are now a number of other optical beam smoothing techniques in addition to ISI - random phase plates (RPP)[6], lens arrays[7], smoothing by spectral dispersion (SSD)[8] and echelon-free ISI[9, 10]. All of the extant beam smoothing techniques achieve much improved illumination uniformity over generic unsmoothed laser beams. There are differences, however, between the various techniques in the extent and nature of the laser bandwidth. The degree of laser bandwidth required to achieve substantial decreases in potentially catastrophic laser-plasma instabilities may be an important criterion determining the use of one or the other of the above-mentioned beam

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smoothing techniques. The RPP approach to beam smoothing does not utilize broad laser bandwidth. The lens array technique does not rely on broad laser bandwidth, but it does not preclude its use. ISI, SSD and echelon-free ISI, on the other hand, all rely heavily on broadened laser bandwidth. They differ in the mechanism by which the bandwidth is generated and possibly in the technological feasibility of achieiving a given degree of bandwidth.

Recent experiments on the backscattered fractions of stimulated Raman and Brillouin scattering have attributed a measured twenty-five fold reductions in instability levels with ISI as compared with RPP to corresponding decreases in the filamentation instability.[11] In the experiments described herein, ISI was observed to reduce the $3\omega_0/2$ and hard x-rays associated with the two-plasmon instability. However, the details of the effects of ISI on the two-plasmon decay instability were very different from that observed with SBS and SRS. At the largest bandwidth used here ($\Delta\lambda$=10 Å at 0.53 μm or $\Delta\omega/2\pi = 1.2\times10^{13}$ sec^{-1}), SBS and SRS were completely suppressed by ISI under our experimental conditions and greatly reduced at an intermediate bandwidth ($\Delta\lambda$=1 Å) – a factor of 10x smaller. In contrast the $3\omega_0/2$ emission was observed to be reduced, but not completely suppressed, only by using ISI with the broadest bandwidths. These results suggest that the mechanism by which ISI affects the two-plasmon decay instability may be different than that for SBS and SRS.

In the two-plasmon decay instability, an incident laser photon at frequency ω_0 undergoes a parametric decay at the quarter-critical density surface into two electron plasma waves or plasmons each at a frequency

approximately equal to $\omega_o/2$. Three-halves harmonic emission occurs when an $\omega_o/2$ plasmon interacts with an ω_o photon in the vicinity of the quarter-critical surface giving a photon at the $3\omega_o/2$ frequency. Tnree-halves harmonic emission from laser-irradiated targets has been extensively studied both theoretically[12-16] and experimentally[17-28]. The importance of the two-plasmon decay to inertial fusion lies in the fact that electrons, accelerated to high energies by electron plasma waves, can preheat the target thus preventing efficient pellet compression.

The threshold for two-plasmon decay instability in a spatially-inhomogenous plasma is given by $(v_o/v_e)^2 k_0 L > \alpha$, where v_o is the electron oscillatory velocity, v_e is the electron thermal velocity, k_0 is the wave number of the pump, L is the density scale length and α=2 to α=4 depending on the value of a parameter $\beta = v_e^4/v_o^2 c^2$.[12,14,15] Hydrodynamic simulations of the effect of the laser-target interactions under our conditions give typical density scale lengths for 0.53 μm irradiation of approximately 150 μm at quarter-critical density and temperatures of 900 eV.[29,30] These parameters give $\alpha \approx 3$ and an intensity threshold for absolute two plasmon decay in the green of 1.3 x 10^{13} W/cm^2. The collisional threshold for the two-plasmon instability is given by the condition that the growth rate $\gamma_o \approx k_o v_o/4$ exceed $\nu_{ei}/2$ where ν_{ei} is the electron-ion collision frequency. Assuming an electron density at the quarter-critical density surface of 1.5 x 10^{21} cm^{-3}, an electron temperature of 900 eV and a $Z_{eff} \approx 5$, the intensity threshold for the collisional two plasmon instability is 1.3 x 10^{13} W/cm^2 – essentially the same as the threshold calculated above for a spatially-inhomogeneous plasma. The present experiment was carried out at time-integrated average intensities between 2.5

x 10^{13} W/cm^2 and 2.5 x 10^{14} W/cm^2, above both the estimated collisional and spatially-inhomogenous two-plasmon decay thresholds.

II. EXPERIMENTAL SET-UP

The experiment was performed with two beams of the Pharos III Nd-glass laser with f/11 focusing lenses. Both beams were frequency converted to the green at 527 nm.[31] The laser pulse duration was 2 nsecs (FWHM) and the energy was varied from 10 J to 250 J on target. One beam contained ISI echelons, the other did not. The ISI beam smoothing used in the present experiment utilized a set of orthogonal transmissive and reflective echelons for spatial incoherence and broad laser bandwidth for temporal incoherence.[1,2] The echelons break the 20 cm diameter laser beam into approximately three hundred 1 cm x 0.8 cm beamlets. Optical delays on the order of two picoseconds were introduced into each adjacent beamlet by incrementing the optical path length in each step of the echelon. If the laser bandwidth $\Delta\omega$ is sufficiently large that the laser coherence time $\tau_c = 2\pi/\Delta\omega$ is shorter than the optical delays introduced by the ISI echelons, then the resulting focal distribution on target will be smooth on time scales long compared to the laser coherence time.

Measurements of $3\omega_o/2$ radiation from the target were taken with the ISI echelons in place at four distinct laser bandwidths covering a range of three orders of magnitude. At the broadest two bandwidths, $\Delta\lambda$=10 Å and 5 Å, the

laser coherence times τ_c satisfied the criteria ($\tau_c \leq 2$ psec) for beam smoothing with our echelons. At the intermediate bandwidth cases, $\Delta\lambda$=1 Å , τ_c is approximately five times greater than the minimum optical delay between beamlets introduced by the ISI echelons, but some residual beam smoothing does occur. Finally in the extreme narrow bandwidth case, in which the laser pulse is time-bandwidth limited, the laser bandwidth is $\Delta\lambda$=0.01 Å. The laser coherence time τ_c here is approximately five hundred times greater than the minimum optical delay introduced by the ISI echelons and the resulting beam intensity profile on target is highly non-uniform.

The experimental configuration of both beams, target, x-ray detectors and harmonic emission detectors are shown in Figure (1). Each beam was incident on a flat 200 µm thick CH target at an angle of 4 degrees to the normal. Measurements of $3\omega_0/2$ emission were also taken at the same four bandwidths for targets irradiated by a beam without ISI echelons. Three fiber-optic collectors each with a 6 cm focal length lens were situated at a distance of 50 cm from the target location at 180, 150, and 130 degree collection angles with respect to the target normal. Quartz fibers from each fiber-optic collection position were input into a 1/4 meter spectrograph whose output was matched to an optical multichannel analyzer (OMA) with a two-dimensional intensified vidicon array operating in a time-integrating mode. Neutral density filters as well as selected bandpass interference filters were used in front of the collection optics. The magnitude of the $3\omega_0/2$ signal for each collection angle was obtained by integrating the OMA detector signal over both the red- and blue-shifted wavelength components. Finally, the Raman backscatter at the 180 degree collection angle was measured with an

array of fast silicon photodiodes with 50 nm bandwidth interference filters centered at 650, 750, 850 and 950 nm.

III. EXPERIMENTAL RESULTS

A. Differences in $3\omega_0/2$ Spectra

Two time-integrated $3\omega_0/2$ spectra at the 150 degree collection angle are shown in Figure (2) for targets irradiated at broad bandwidth and narrow bandwidth ($\Delta\lambda$=10 and 0.01 Å) at intensity approximately equal to 7.5×10^{13} W/cm^2. The peak of the $3\omega_0/2$ emission in the spectrum with the narrow bandwidth laser is almost two orders of magnitude greater than in the spectrum obtained with broad bandwidth. In addition the measurements show a significant difference in the relative amplitudes of the red and blue components of the $3\omega_0/2$ spectrum. The $3\omega_0/2$ spectrum from the narrow bandwidth case contains a blue component with a magnitude less than 10% that of the red component, whereas in the broad bandwidth case the blue component is over 50% the amplitude of the red component. Although the effect of broad bandwidth ISI is to reduce the overall level of emission, the red component carrying most of the energy seems to be damped more strongly than the blue component. The wavelength shift from the nominal $2\lambda_0/3$ value for the red and blue components is virtually the same for the two shots.

B. Relative Amplitudes of the $3\omega_0/2$ Emission

The use of broad bandwidth ISI results in a significant reduction in the overall level of the $3\omega_0/2$ radiation. Figure (3) shows the effect of bandwidth variation in conjunction with ISI echelons on the overall level of the $3\omega_0/2$ emission observed at the 180 and 150 degree collection angles. The incident laser intensity was determined by fitting densitometer line-outs of the equivalent focal plane distribution to the ideal ISI intensity profile $I=I_0 \mathrm{sinc}^2(2\pi x/d)$ and then calculating the average intensity within the full width at half-maximum where d is the diffraction envelope width. The use of broad laser bandwidth ($\Delta\lambda$=10 Å and 5 Å) reduced not only the amplitude of the $3\omega_0/2$ emission as compared with the intermediate ($\Delta\lambda$=1 Å) and narrow bandwidth ($\Delta\lambda$=0.01 Å) cases, but also the rate of increase of the amplitude with increasing average laser intensity. Data points in Fig. (3) indicated by upward arrows may be below the actual values by as much as a factor of two due to detector saturation, however this does not alter the qualitative picture described above.

In the limit of bandwidth $\Delta\omega$ much greater than the growth rate γ ($\Delta\omega \gg \gamma$), Thomson's theoretical treatment of bandwidth effects on parametric instabilities predicts that reductions in growth rates by a factor $\gamma/\Delta\omega$ can be achieved.[32] Although Thomson's theory includes temporal bandwidth only whereas ISI involves both spatial and temporal incoherence, it is interesting to examine the predicted effects of bandwidth alone. The maximum two plasmon decay growth rate is given by $\gamma=k_0 v_0/4$.[12-15] At the parameters of the present experiment, the maximum growth rate at incident laser intensities of 1×10^{14} W/cm^2 is $\gamma=5.7 \times 10^{12}$ sec^{-1} compared with values of bandwidth of 3.45×10^{12} sec^{-1} for the $\Delta\lambda$=5 Å case and 6.68×10^{12} sec^{-1} for the $\Delta\lambda$=10 Å case.

At the irradiances of the experiment reported here, the growth-rate of the two-plasmon decay instability is roughly comparable or only slightly less than the largest laser bandwidths - a region where present theories of the effects of bandwidth on parametric instabilities do not strictly apply.

Experiments have been reported showing suppression of $3\omega_0/2$ emission in filamentary channels using broad bandwidth (30 Å), low energy (10 J) and short pulses at 1.06 μm.[25] In that study, however, time-integrated laser intensity distributions at an equivalent focal plane appear highly nonuniform for narrow bandwidth and smooth at broad bandwidth suggesting that the combination of low f# optics and chromatic aberration of the final focussing lens may have smoothed the laser profile in a manner analogous to ISI. It is therefore unclear whether the reported suppression of the harmonic emission in that experiment can be attributed to bandwidth or beam-smoothing effects. Similarly in the present experiment, it is not possible to clearly distinguish between bandwidth and beam-smoothing effects because of the large illumination nonuniformities present in both the ISI-echelon beam at narrow bandwidth and the non-echelon beam at all bandwidths. Nonetheless it is interesting to examine the intensity dependence of the $3\omega_0/2$ emission at the four bandwidths for a laser with no ISI echelons.

A comparison of results at the four bandwidths with a regular beam (no echelons) is shown in Figure (4) for the 130 degree collection angle. The laser intensity given here is the average value over the flat-top portion of the intensity pattern at the equivalent focal plane. The three-halves harmonic emission levels in Fig. (4) show little difference between the four bandwidths.

At the lower intensities in particular, where the ratio of growth rate to bandwidth is the smallest, and the largest finite bandwidth effect might be expected, virtually no difference between broad and narrow bandwidths in the $3\omega_0/2$ emission is observed on the no-echelon beam. The slopes and amplitudes for the $3\omega_0/2$ emission across all four bandwidths for the no-echelon beam are comparable to the intermediate and narrow bandwidth with the ISI echelon beam. In the presence of large illumination nonuniformities characteristic of the no-echelon beam, broad bandwidth alone does not reduce the level of the underlying two plasmon decay instability. As in Fig. (3) above, data points in Fig. (4) indicated by upward arrows may be below the actual values by as much as a factor of two due to detector saturation.

C. Raman and Hard X-Ray Data

An array of photodiode detectors with narrow band interference filters as well as time-integrated spectroscopy were used to monitor Raman spectra in the region 6500 Å to 9500 Å. The peak Raman signal was obtained near the 750 nm wavelength. Copious Raman emission was observed for both the non-echelon beam at all bandwidths and the ISI-echelon beam at the narrowest bandwidth $\Delta\lambda$=0.01 Å. Finally, time- and space-integrated hard x-ray measurements were also made using a set of silicon p-i-n diodes and scintillator/photomultiplier detectors with broadband k-edge filtering techniques. The hard x-ray signals were fit to a Maxwellian energy

distribution and the energy in hot electrons determined accordingly following the procedure outlined by Keck.[33] Figure (5) shows the correlation between the x-ray data and the $3\omega_0/2$ data at 130 degrees at the broad bandwidth (10 Å) and the intermediate bandwidth (1 Å) for the ISI-echelon beam.

Hard x-rays produced by suprathermal electrons undergoing collisions with the cooler background plasma can be a signature of either Raman or two-plasmon decay.[33] In contrast to the x-ray data and the $3\omega_0/2$ data, the Raman spectra was nearly completely suppressed at the $\Delta\lambda$=1 Å bandwidth in agreement with earlier reported results.(7) Figure (6) compares the Raman backscatter near 750 nm and the $3\omega_0/2$ emission backscatter for an ensemble of shots with incident laser intensity from 7.5 x 10^{13} W/cm^2 to 1.40 x 10^{14} W/cm^2. There is significant reduction of Raman at narrow bandwidth (1 Å) in contrast with the $3\omega_0/2$ radiation which did not exhibit any substantial reduction in emission amplitude except at full laser bandwidth (10 Å). A similar bandwidth effect to that observed with Raman was also seen with simulated Brillouin.[5] Although three-halves harmonic radiation can be generated from Raman ocurring at $n_c/4$ as well as two plasmon decay, the lower threshold and the characteristic red and blue spectral components of the emission observed in the present suggest that the two plasmon decay is responsible for the observed $3\omega_0/2$ emission.[17] The anti-correlation between the x-ray and Raman data for the $\Delta\lambda$=1 Å bandwidth is additional evidence that two-plasmon decay at quarter-critical is indeed the instability responsible for the x-rays as well as the $3\omega_0/2$ emission. It is interesting to note that the maximum theoretical growth rate for Raman is comparable to two-plasmon. If temporal bandwidth alone were important for both instabilities, one might

expect instability amplitude reduction for both at the same bandwidth. The observed difference in bandwidth effect on Raman and $3\omega_0/2$ emission shown in Figure (6) may be due to differences in intensity thresholds for the two instabilities as well as differences in the nature of the instabilities (absolute versus convective). A recent paper by Guzdar et al. on the effect of ISI on absolute Raman has suggested that the effect of bandwidth variation may affect absolute instabilities differently than convective instabilities.[34] This issue is further complicated by the observation made with unsmoothed lasers that Raman occuring well below quarter-critical density may be an absolute instability associated with density fluctuations in the plasma. [35] At present there is no well-established theory that can explain these phenomena.

IV. SUMMARY AND CONCLUSIONS

Theoretical and numerical studies indicate that ISI can suppress filamentation at 0.53 μm for intensities comparable to those in the present experiment.[30] In both the present and previous experiments at the intermediate (1 Å) bandwidth, the reduction of SRS and SBS has been attributed at least in part to the predicted decrease in filamentation with ISI.[3,5] In the case of two plasmon decay, however, neither the $3\omega_0/2$ emission nor the hard x-rays are reduced until the bandwidth is increased an additional factor of five to ten times ($\Delta\lambda$=5 and 10 Å), hence it is possible that the reduction of the instability is due as much to direct bandwidth effects on the instability as to the absence of filamentation. The experimental observation that larger bandwidth is required to suppress two-plasmon decay than SRS or SBS is in qualitative agreement with a recent theoretical analysis of the direct

effect of ISI on parametric instabilities, especially at the quarter-critical density surface.[36] The strong correlation between the x-ray data and the $3\omega_0/2$ emission suggests further that the observed reduction in the three-halves harmonic emission is related to reduction in the underlying two-plasmon decay instability rather than the harmonic generation process.

In conclusion, we have made the first detailed study of the two plasmon decay instability as inferred from $3\omega_0/2$ and hard x-ray emission with and without ISI echelons over a range of bandwidths at intensities relevant to laser fusion. The use of ISI echelons at broad bandwidths leads to significant decreases in the level of emission as compared with both no-echelon beams and echelon beams with intermediate and narrow laser bandwidths. In contrast to SRS and SBS, however, two plasmon decay is not completely suppressed by broad bandwidth and ISI. As in the previous ISI interaction experiments, it is not clear whether the observed reduction in plasma instabilities with ISI is due to decrease in filamentation or whether there is an additional effect due to bandwidth. The difference between two-plasmon and other previously observed laser-plasma instabilities discussed above, however, suggests that very large bandwidth may be important for interaction physics with any beam-smoothing technique.

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[a]Science Applications International Corp., McLean, VA 22102 ; present address: Charged Particle Physics Branch, Naval Research Laboratory, Washington, DC 20375-5000

[b]Present address: Space Plasma Branch, Naval Research Laboratory, Washington, DC 20375-5000

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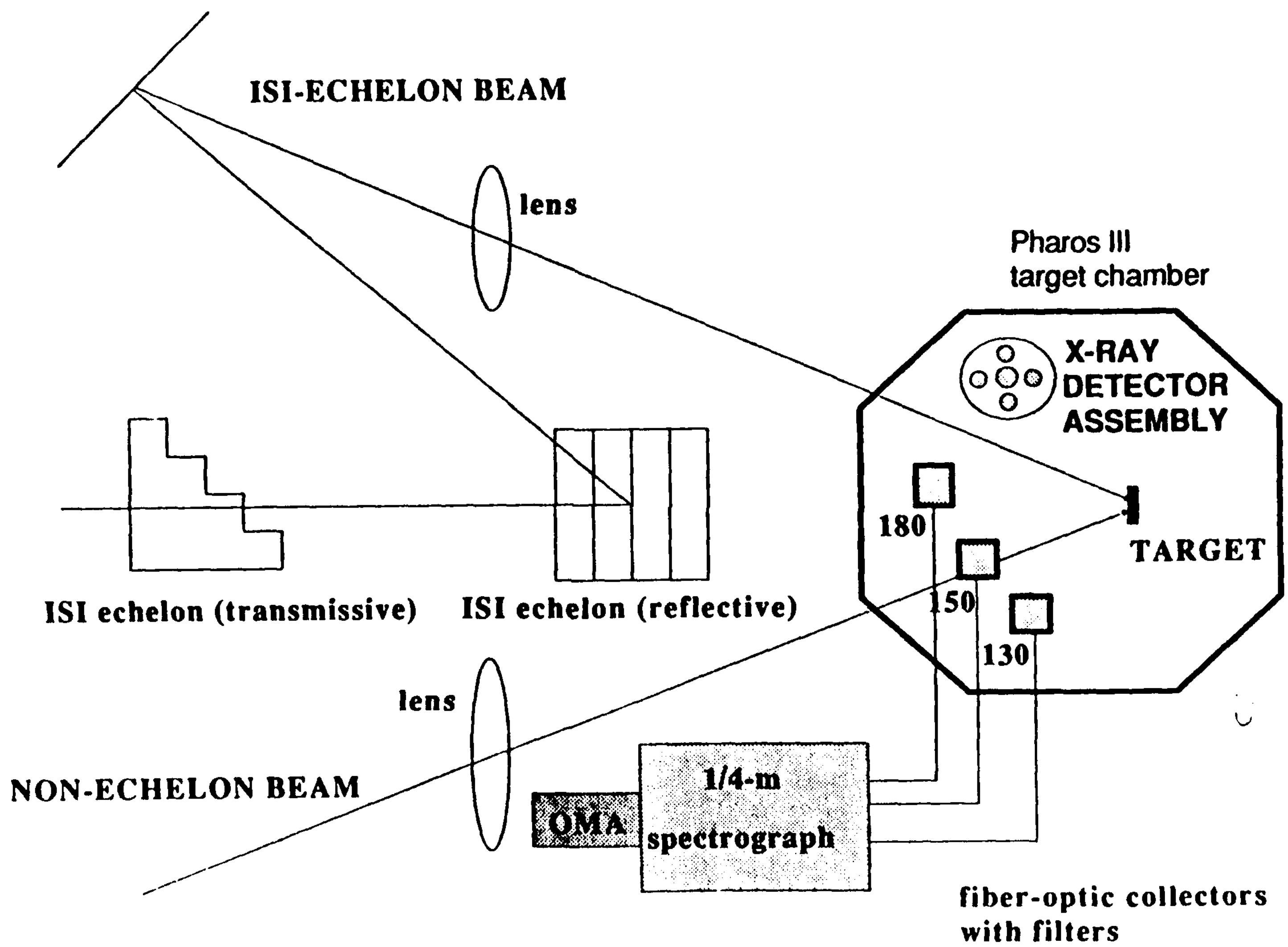

Fig. 1 — Experimental arrangement for $3\omega_o/2$ ISI interaction experiment showing two beams, with and without ISI echelons, and position of the fiber optic $3\omega_o/2$ collectors, spectrograph and OMA as well as the x-ray detector assembly

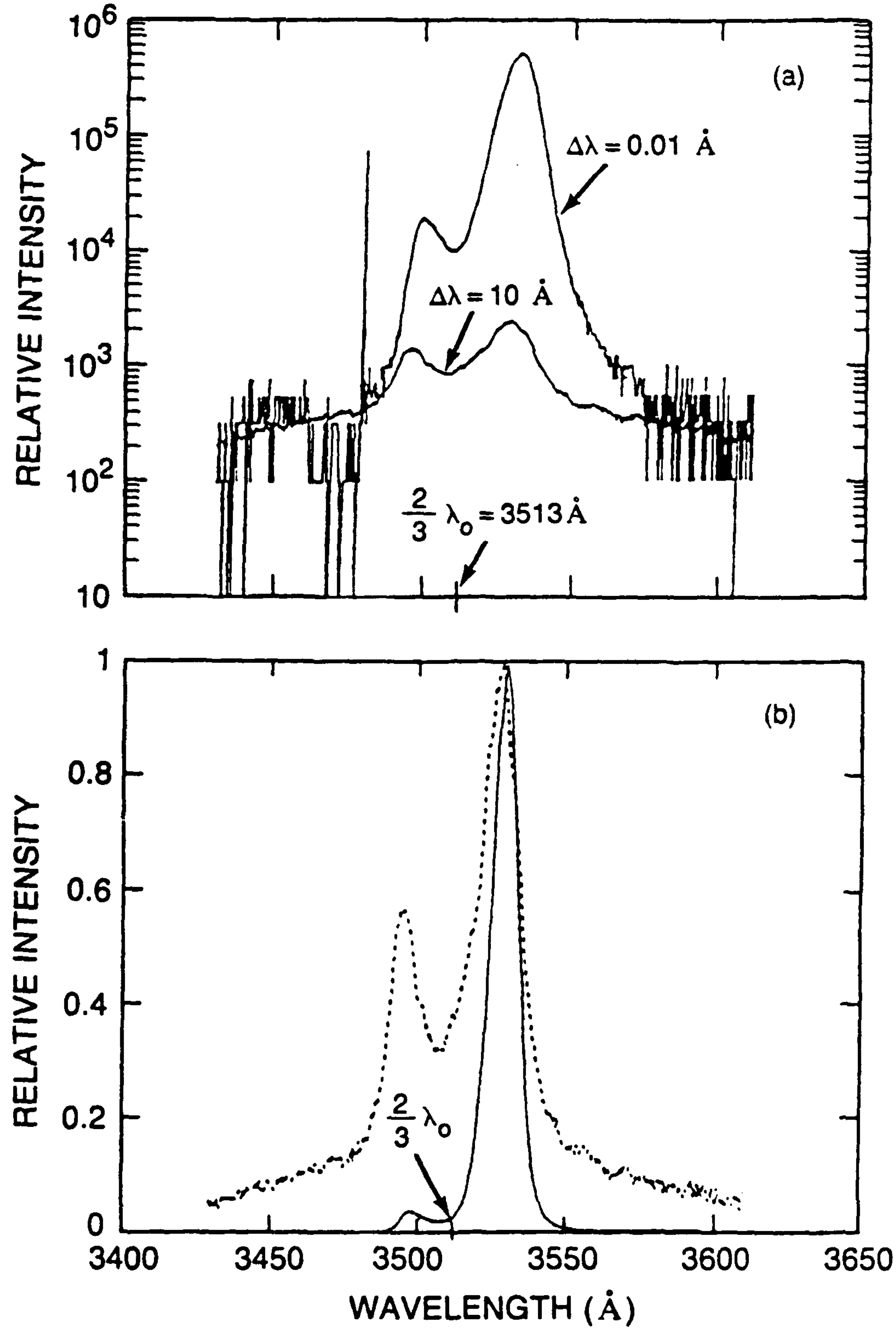

Fig. 2 — (a) Time-integrated spectra of the $3\omega_o/2$ emission at the 150 degree observation angle for two shots with ISI echelons: one, at narrow bandwidth 0.01 Å; the other, broad bandwidth 10 Å; (b) The same spectra, narrow bandwidth 0.01 Å (______) and broad bandwidth 10 Å (------) shown normalized to their maximum values. The wavelength corresponding to the $3\omega_o/2$ frequency is indicated as $2\lambda_o/3$.

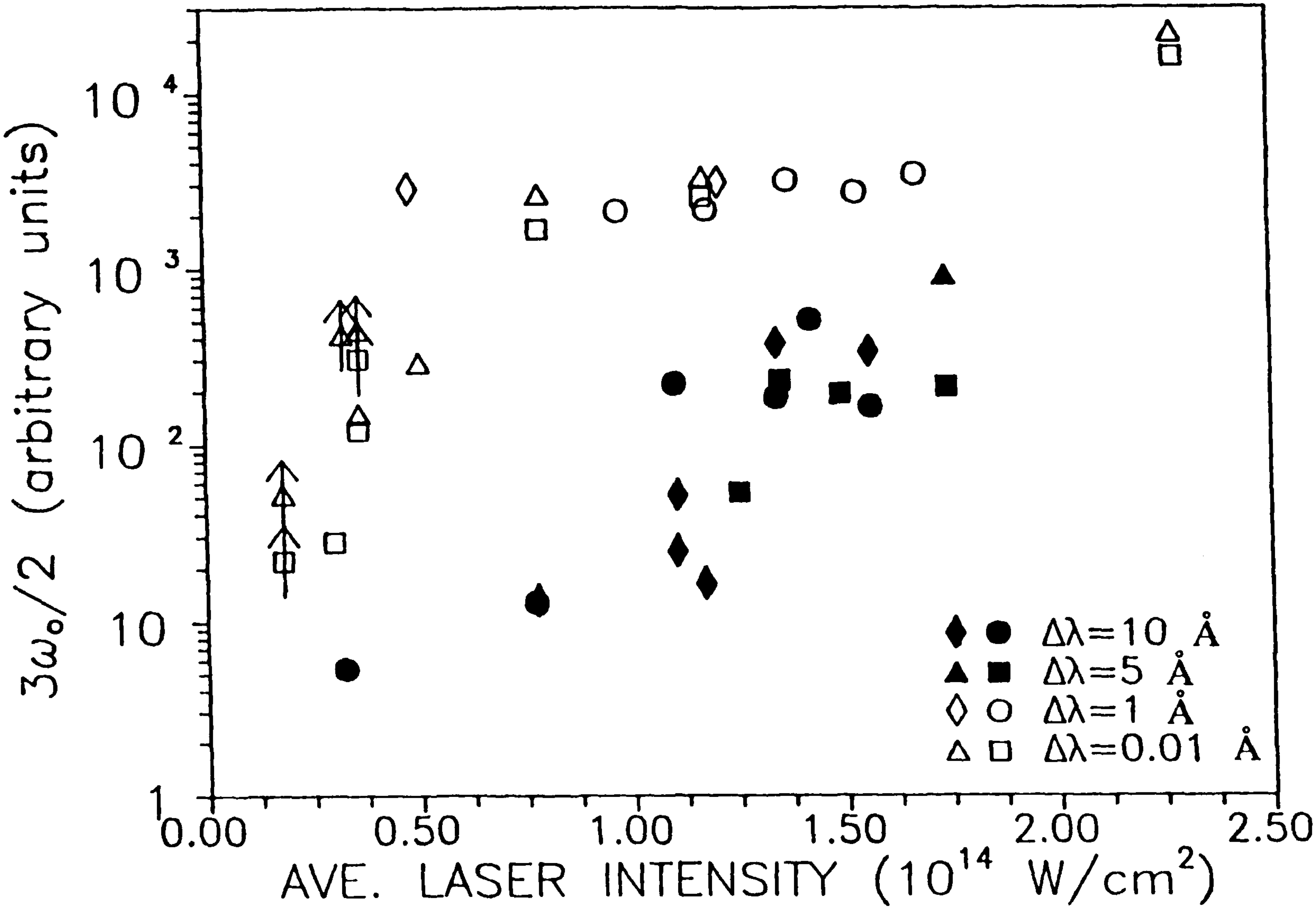

Fig. 3 – Time and spectrally-integrated $3\omega_o/2$ signal for beam with ISI echelons at four bandwidths for two collection angles: circles and squares denote 180 degrees, diamonds and triangles denote 150 degrees

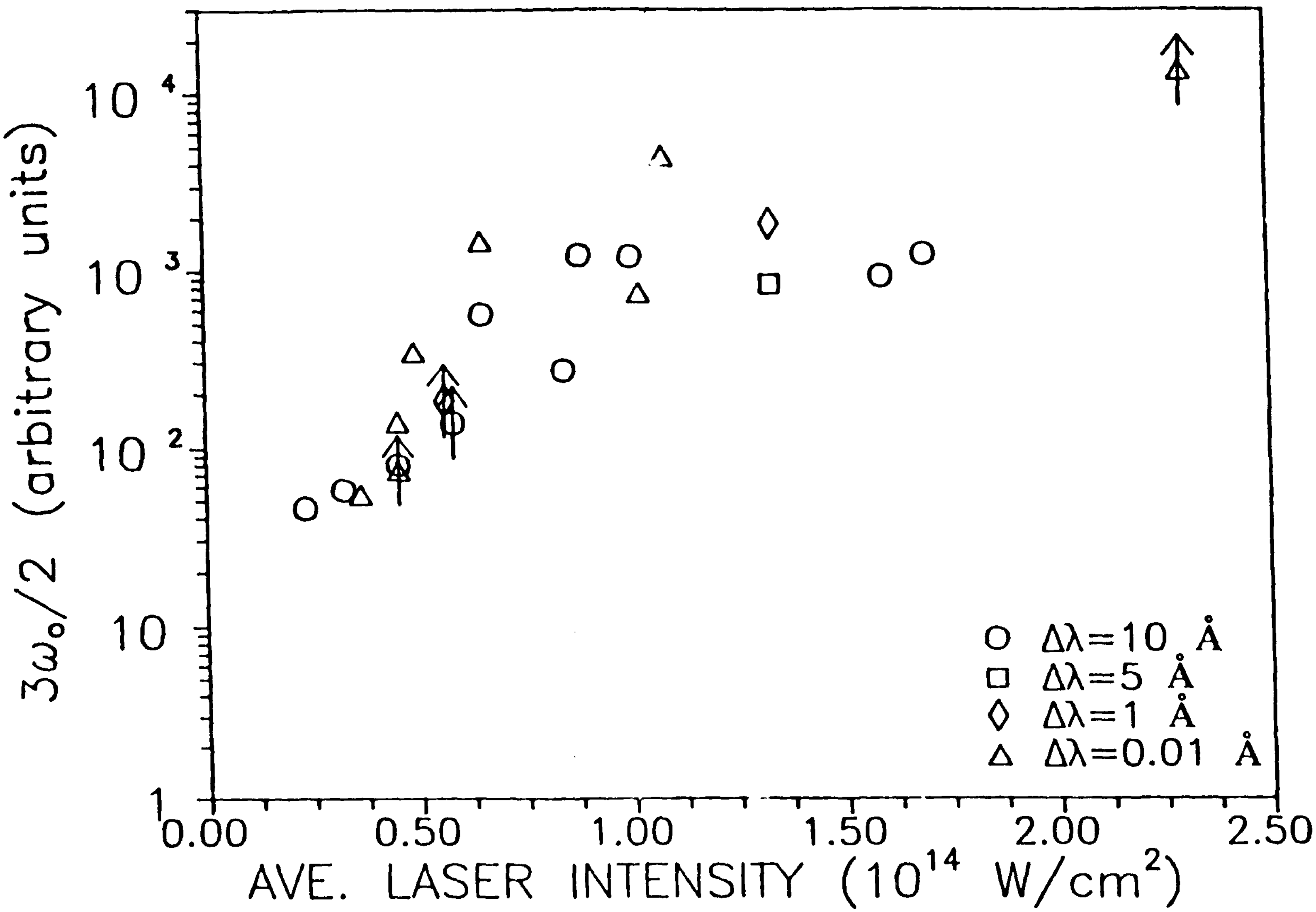

Fig 4 — Comparison of time and spectrally-integrated $3\omega_o/2$ signal for the beam without echelons at four bandwidths for the collection angle of 130 degrees with respect to the target normal

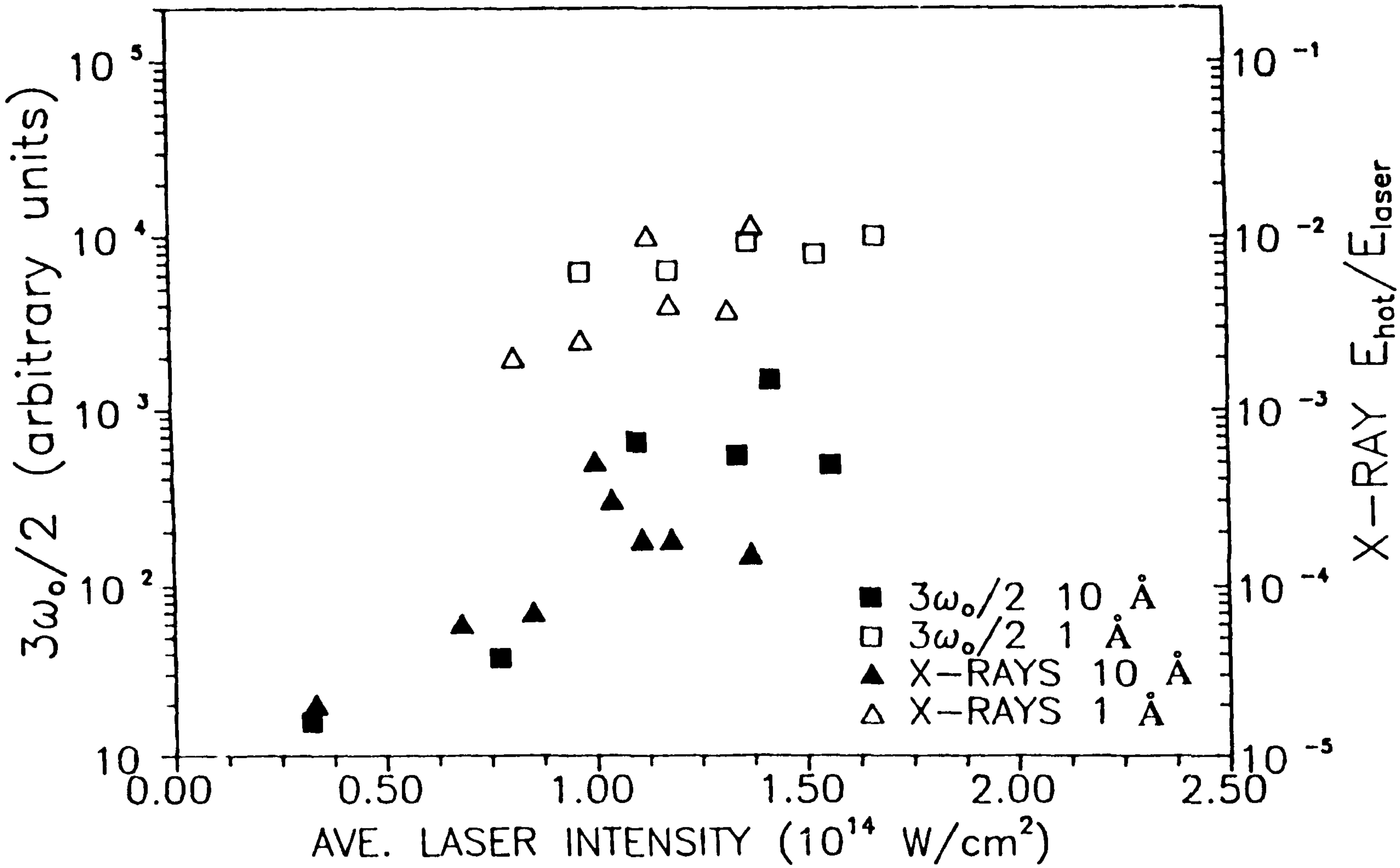

Fig. 5 – Correlation between time- and space-integrated hard x-ray measurements (ratio of hot electron energy to the incident laser energy) and the 130 degree collection angle $3\omega_o/2$ data at broad bandwidth (10 Å) and narrow bandwidth (1 Å) for the ISI-echelon beam

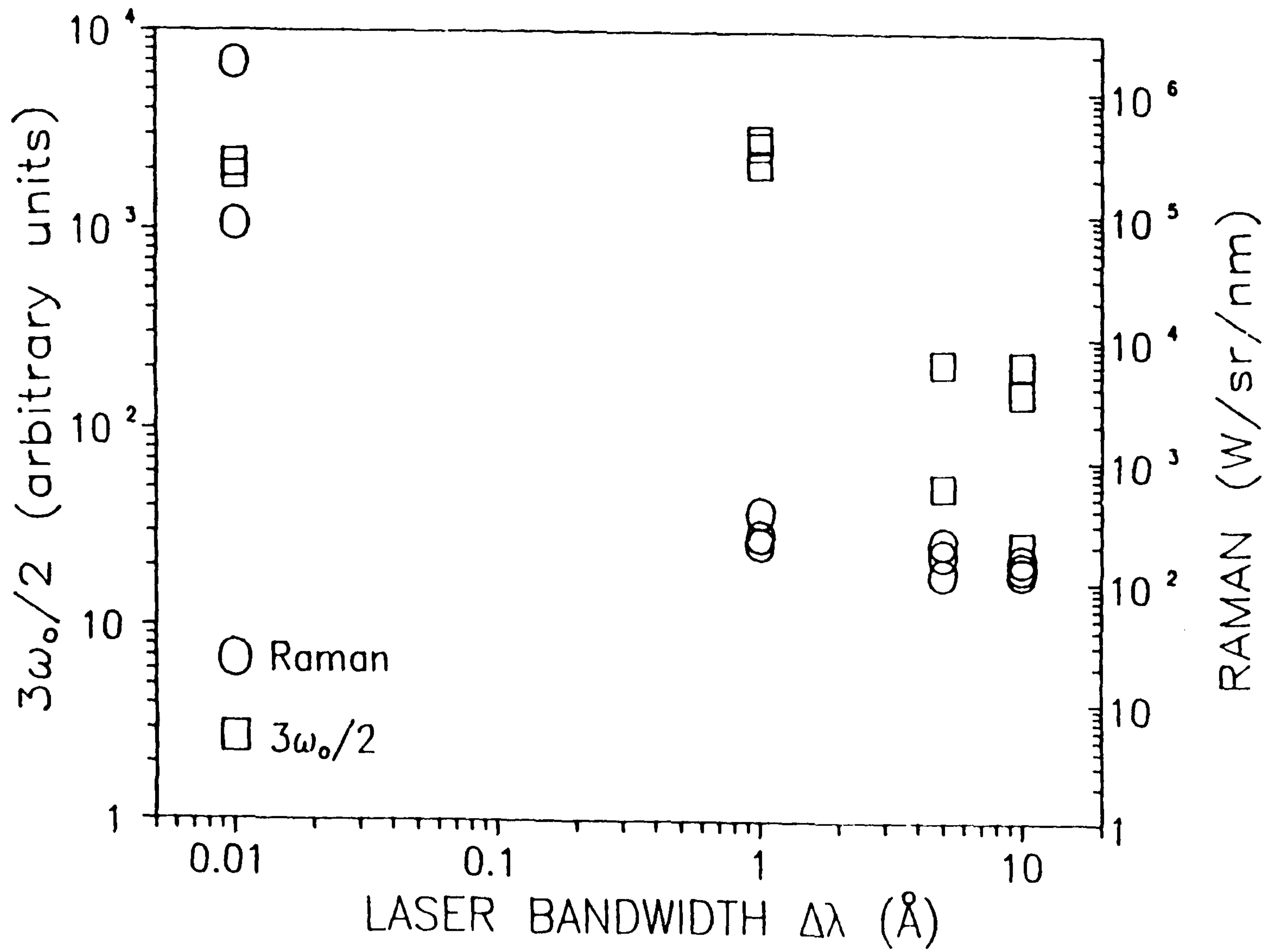

Fig. 6 — Comparison of Raman and $3\omega_o/2$ signal levels at four bandwidths for an ensemble of shots with incident intensity I between 7.5×10^{13} W/cm^2 and 1.40×10^{14} W/cm^2 showing significant reduction of Raman at narrow bandwidth (1 Å) compared with $3\omega_o/2$ which did not exhibit any substantial reduction in emission amplitude except at full laser bandwidth (10 Å)